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Development of a simple-structured pneumatic robot arm and its control using low-cost embedded controller

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Abstract

The purpose of our study is to develop the flexible and lightweight actuator and apply it into a flexible robot arm. In this paper, the master-slave attitude control and the trajectory control of the flexible robot arm are proposed. This robot arm has three degree-of-freedom that is bending, expanding and contracting and will be applied into a rehabilitation device for human wrist. The master-slave control system which is proposed in this paper is necessary when a physical therapist wants to give a rehabilitation motion to a patient. While the trajectory control system is necessary when a sequential rehabilitation motion is applied to a patient. In this paper, an analytical model of a flexible robot arm is proposed for master-slave attitude control and trajectory control. Then, a compact and inexpensive control system is developed and tested. The system consists of a flexible robot arm, a low-cost embedded controller, accelerometers and small-sized quasi-servo valves which are developed by using the on/off control valve in our laboratory. The results from these experiments demonstrate that the master-slave attitude control can be realized by using an accelerometer and a simple analytical model of the robot arm. The trajectory control also was realized for a square trajectory by using an analytical model and a compact control system. The error between the desired trajectory and measured one is relatively large compared with typical robot arm. This is because by a friction that is existing in a rod-less type flexible pneumatic cylinder. The control performance can be improved by reducing the friction or by improving the control scheme.

Keywords: Pneumatic robot arm; Flexible pneumatic cylinder; Rehabilitation device; Master-slave control; Trajectory control;

Nomenclature

A	matrix of the robot arm	V_x, V_y, V_z	output voltages from accelerometer (V)
e	deviation of the cylinder length (m)	X_c, Y_c, Z_c	coordinates of the robot arm end (m)
K_P	proportional gain (%/m)	α	bending direction angle (rad)
K_I	integral gain (%/m/s)	β	bending angle (rad)
K_D	differential gain (%/s/m)		
L	"cylinder length" (displacement) (m)	Subscripts:	
r	distance from the centre of the ring-shaped stage to the centre of the slide stage in the cylinder (m)	m	master arm
		s	slave arm
R	radius of curvature of the cylinder (m)	0	backbone tube
u	control input (duty ratio) (%)	$1,2,3$	location number of the flexible cylinder

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1. Introduction

In an aging society with fewer children, it is strongly desired to develop a system to aid in nursing care [1],[2] and to support the activities of daily life for the elderly and the disabled [3]. The actuators need to be flexible so as not to injure the human body [4]. We have been aiming at developing a flexible and lightweight actuator and applying it into the flexible robot arm, the rehabilitation device and so on. So far, we have proposed and tested the new types of flexible pneumatic actuator that can be used even if the actuator is deformed by external forces [5] such as flexible pneumatic rotary actuator [6]. We have also proposed and tested a flexible robot arm with simple structure by using of the rod-less type flexible pneumatic cylinders as shown in Fig. 1(a) [7]. This robot arm has three degree-of-freedom that is bending (2-DOF) and expanding-and- contracting (1-DOF). This arm has a potential to be used as a rehabilitation device for human wrist.

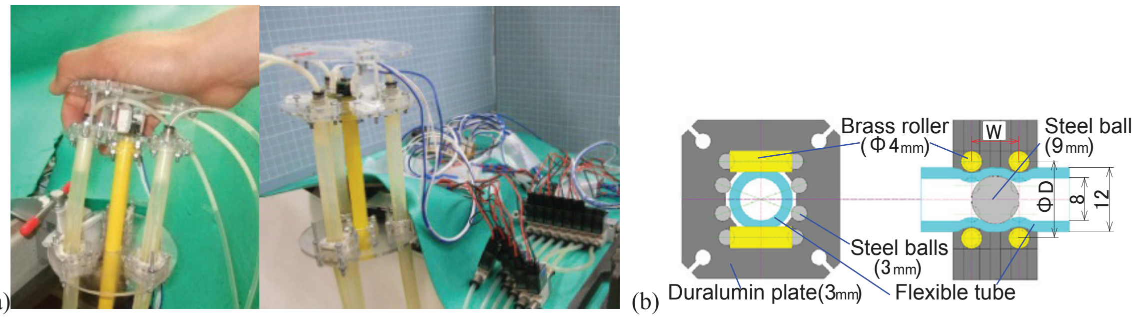
When the robot arm is applied to a rehabilitation device, two kinds of control method will be needed. One is a master-slave control, and the other is a trajectory control. The master-slave control which is proposed by this paper is necessary when a physical therapist wants to give a rehabilitation motion to a patient. While the trajectory control system is necessary when a sequential rehabilitation motion is applied to a patient. We also propose the analytical models of the flexible robot arm for the attitude master-slave control and the trajectory control. Then, a compact and inexpensive control system is constructed and tested by using the low-cost embedded controller. The control system consists of a flexible robot arm, a low cost microcomputer, accelerometers, and small-sized quasi-servo valves which are developed by us using the on/off control valve [8]. Finally, the experimental results of two kinds of control method which is master-slave control and trajectory control are presented and the effectiveness of these control methods is confirmed.

2. Flexible Cylinder and Robot arm

2.1. Rod-less type flexible pneumatic cylinder

Fig. 1(b) shows the construction of a rod-less type flexible pneumatic cylinder. It consists of a flexible tube as a cylinder, one steel ball as a cylinder head and a slide stage that can slide along the outside of the tube. The steel ball is pinched by two pairs of brass rollers from both sides of the ball. The operating principle of the rod-less type flexible pneumatic cylinder is the inner steel ball will be pushed up or down when we supply pressure to one side of the cylinder. At the same time, the steel ball pushes the brass rollers and then the slide stage moves while it deforms the tube. In the previous research, we had investigated various numbers for distance D and distance W (shown in Fig. 1(b)) by using the minimum driving pressure of the rod-less type flexible pneumatic cylinder. From that experiment, we found the best value for D is 14.4mm and for W is 10mm [6].

(a)



(b)

Fig. 1. Picture of flexible pneumatic robot arm for (a) tested robot arm using flexible cylinders and (b) construction of flexible pneumatic cylinder

Table 1 shows the properties of the flexible pneumatic cylinder that have been used for our pneumatic robot arm. The specifications of the cylinder such as a minimum radius of curvature for the cylinder, the maximum working pressure and an allowable working temperature are depended on the properties of the soft polyurethane tube (SMC Co Ltd(TUS 1208).

2.2. Flexible robot arm

Fig. 2 shows the construction of flexible robot arm by using flexible pneumatic cylinders. The robot arm consists of two ring-shaped stages and three flexible pneumatic cylinders with the slide stages. The outer diameter of the ring-shaped stage is 100mm and the initial distance between the upper and lower ring-shaped stage is about 100mm. Each flexible pneumatic cylinder is arranged so that the central angle of two adjacent slide stages becomes 120 degrees on a ring-shaped stage. The edge of each flexible cylinder also is fixed in the upper ring-shaped stage. Two on/off control valves (Koganei Co. Ltd., G010HE-1) or quasi-servo valves are used to drive one flexible pneumatic cylinder.

Table 1. Properties of flexible pneumatic cylinder

Min. driving pressure	120kPa
Generated force	16N(input:500kPa)
Max. moving speed	> 1m/s
Weight (stroke of 1m)	< 0.1kg
Min. radius of curvature	about 30mm
Max. working pressure	600kPa
Working temperature	From -20 to +60 deg.C
Movement	Push-pull actions

In order to control the pneumatic flexible robot arm, we have used six quasi-servo valves. This robot arm has a flexible tube in the centre of the ring-shaped stage as a backbone. One end of the backbone tube is connected with the upper ring-shaped stage and the other end is connected with the lower ring-shaped stage. For the backbone which is connected with the upper ring-shaped stage only, the robot arm can bend, expand and contract. While the others end of the backbone which is connected with lower ring-shaped stage, the arm can bend only.

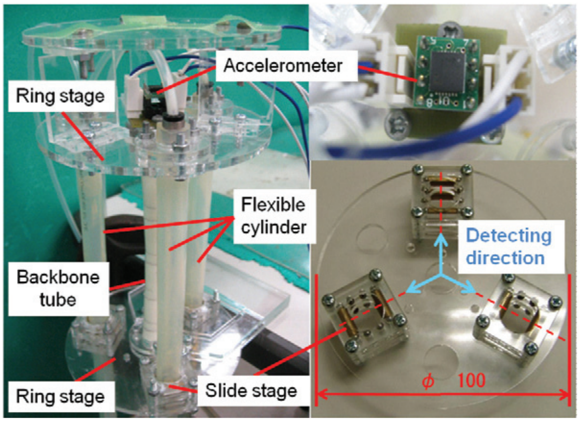


Fig. 2. Construction of flexible robot arm

3. Analytical Model for Control

3.1. Master slave control (Arm model 1)

Fig. 3 shows an analytical model for the master-slave attitude control of a flexible robot arm. In this model, we assume that the shape of each flexible pneumatic cylinder becomes a circular arc when the arm bends. From the geometrical relationship shown in Fig. 3, the desired length (in a master arm) and the present length (in a slave arm) of each cylinder L are calculated by the following Eqs. (1)-(4) using the bending direction angle α and the bending direction angle β. Fig. 3 (b) shows the definition for the bending direction angle α and β.

$$L_{1i} = \left(R_i - r \cdot \cos\alpha_i\right) \cdot \beta_i \qquad \text{(i=m,s)} \qquad (1)$$

$$L_{2i} = \{R_i - r \cdot \cos(\frac{2\pi}{3} - \alpha_i)\} \cdot \beta_i \qquad \text{(i=m,s)} \qquad (2)$$

$$L_{3i} = \{R_i - r \cdot \cos(\frac{4\pi}{3} - \alpha_i)\} \cdot \beta_i \qquad \text{(i=m,s)} \qquad (3)$$

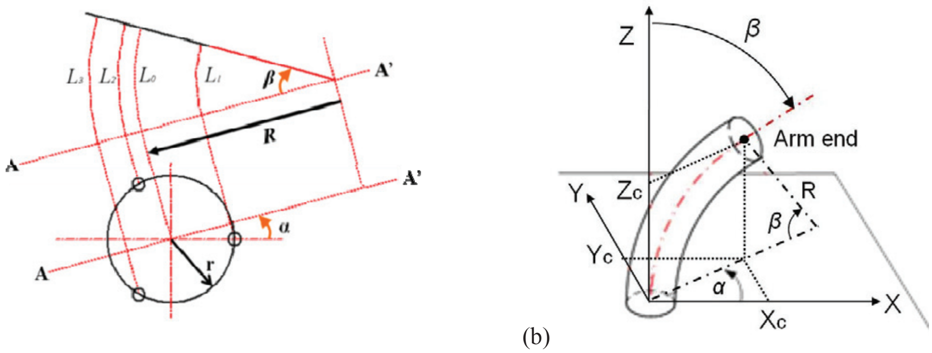
$$R_i = \frac{L_{0i}}{\beta_i} \qquad \text{(i=m,s)} \qquad (4)$$

Where L_0 means the length of a backbone tube installed between the upper and lower ring-shaped stage which is 100mm fixed. Subscripts m and s indicate the desired (master arm) and the present (slave arm), subscript number (1, 2, 3) indicates the location number of the cylinder, R is the radius of curvature of the cylinder, and r which is 33 mm fixed is the distance from the centre of the ring-shaped stage to the centre of slide stage in the cylinder. The value for the bending direction angle α and the bending angle β are given by following equations which are using the output voltage from the accelerometer.

$$\alpha_i = \cos^{-1} \frac{V_{xi}}{\sqrt{V_{xi}^{\ 2} + V_{yi}^{\ 2}}} \qquad \text{(i=m,s)} \qquad (5)$$

$$\beta_i = \cos^{-1}(\frac{V_{zi}}{V_{z\max i}}) \qquad \text{(i=m,s)} \qquad (6)$$

V_x, V_y, and V_z are the output voltages from the accelerometer. The voltages V_x and V_y correspond to the angle from the horizontal plane and V_z corresponds to the angle from the vertical plane. The V_{zmax} means the difference of V_z between the values in horizontal and vertical planes. By using Eqs. (1)-(6), we can calculate the length of six cylinders for every bending state of the robot arm. In our previous study, we had confirmed that the calculated angle agreed well with the measured value [7]. The error between the master angles and slave angles was less than 1 degree.



(a) (b)

Fig. 3. Analytical model for (a) attitude control and (b) definition of attitude angles

3.2. Trajectory control (Arm model 2)

As in the preceding section, we assume that the shape of each flexible pneumatic cylinder becomes a circular arc when the arm bends. From the geometrical relationship in Fig. 3(b), the coordinates (X_c, Y_c, Z_c) of robot arm end and the radius of curvature R can be expressed as below.

$$X_c = R \cdot (1 - \cos\beta)\cos\alpha \qquad (7)$$

$$Y_c = R \cdot (1 - \cos\beta)\sin\alpha \qquad (8)$$

$$Z_c = R \cdot \sin\beta \qquad (9)$$

$$R = \frac{L}{\beta} \qquad (10)$$

Next, these equations are linearized around the equilibrium point for a trajectory control. Let $X_c = X_{c0} + \delta X_c$, $Y_c = Y_{c0} + \delta Y_c$, $\alpha = \alpha_0 + \delta\alpha$, $\beta = \beta_0 + \delta\beta$, and $L = L_0 + \delta L$. By substituting these relations to Eqs. (7)-(10) and carrying out the linear approximation, the following equations are obtained.

$$\begin{bmatrix} \delta X_c \\ \delta Y_c \\ \delta Z_c \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} \delta\alpha \\ \delta\beta \\ \delta L \end{bmatrix} \tag{11}$$

Where, the elements of the matrix $\boldsymbol{A}$ can be given as

$$\begin{aligned} &A_{11} = \frac{L_0 \cdot \sin\alpha_0 \cdot (\cos\beta_0 - 1)}{\beta_0}, \quad A_{12} = \frac{(L_0 \cdot \sin\beta_0 \cdot \cos\alpha_0 - X_{c0})}{\beta_0} \\ &A_{13} = \frac{(1 - \cos\beta_0) \cdot \cos\alpha_0}{\beta_0}, \quad A_{21} = \frac{L_0 \cdot \cos\alpha_0 \cdot (1 - \cos\beta_0)}{\beta_0} \\ &A_{22} = \frac{(L_0 \cdot \sin\beta_0 \cdot \sin\alpha_0 - Y_{c0})}{\beta_0}, \quad A_{23} = \frac{(1 - \cos\beta_0) \cdot \sin\alpha_0}{\beta_0} \\ &A_{31} = 0, \quad A_{32} = \frac{(L_0 \cdot \cos\beta_0 - Z_{c0})}{\beta_0}, \quad A_{33} = \frac{\sin\beta_0}{\beta_0} \end{aligned} \tag{12}$$

Finally, by multiplying the inverse matrix $\boldsymbol{A}^{-1}$ to Eq. (11) from the left side, the following equation can be obtained.

$$\begin{bmatrix} \delta\alpha \\ \delta\beta \\ \delta L \end{bmatrix} = A^{-1} \cdot \begin{bmatrix} \delta X_c \\ \delta Y_c \\ \delta Z_c \end{bmatrix} \tag{13}$$

By using Eq. (13), we can calculate the variations of bending direction angles α, bending angles β and cylinder length ($\delta\alpha, \delta\beta, \delta L$) respectively, if we are given the variations value of arm end coordinate ($\delta X_c, \delta Y_c, \delta Z_c$).

4. Control System and Procedure

4.1. Master slave control

We tried to construct the control system as compact and inexpensive as possible. Fig. 4 shows the schematic diagram of the master-slave control system. It consists of a slave arm and a master arm. The slave arm consists of the tested robot arm that is mentioned above, an accelerometer, a microcomputer (Renesas Co. Ltd., SH7125) and six quasi-servo valves. The master arm consists of an accelerometer that is set on the top of a flexible tube to give the reference attitude value. The attitude of the upper ring-shaped stage is detected with the accelerometer which has installed in the upper ring-shaped stage. The accelerometer can detect the bending angle of the upper stage by measuring the change of gravity for X, Y, and Z axis.

From these values, the bending direction angle α and the bending angle β are calculated by Eq. (5) and Eq. (6). The master-slave control system of the tested flexible robot arm can be understood by examining the diagram in Fig. 4. Fig. 5 shows the block diagram of the master-slave control system. The microcomputer gets the output voltage from the bending angles and calculates the desired length and the present length of each flexible cylinder by using Eqs. (1)-(4). The "length of the flexible cylinder" can be defined as the distance between the upper ring-shaped stage and the lower stage. By using this method, we can control the each length of the cylinder as a position control. As a result, the master-slave control system can be realized. The variables output from microcomputer needs to be converted from digital signal into the analog signal in order to record it. So, we had developed the D/A converter and record the variables output voltage such as for angle and displacement by using GRAPHTEC, GL200 recorder.

4.2. Trajectory control

The trajectory control system is the system which does not have the master arm. In this system, we only use the slave arm. The block diagram of trajectory control system is shown in Fig. 6. The control procedure is as follows. 1) First, the desired trajectory of the robot arm end is generated. 2) By using the output voltages of an accelerometer and a potentiometer, the present bending direction angle α, the bending angle β and the length L_0 can be confirmed and calculated. At the same time, the present cylinder lengths L_1, L_2 and L_3 are also calculated by using Eqs.(1)-(4). 3) Then, by the difference between the present position of arm end and the desired position, the variations ($\delta X_c, \delta Y_c, \delta Z_c$) of arm end coordinate are calculated. The variations ($\delta\alpha, \delta\beta, \delta L$) are calculated by using Eq.(13). From this equation, α_1, β_1 and L_{01} can be obtained and the desired positions are calculated. The desired cylinder lengths L_{11}, L_{21} and L_{31} are calculated by arm model 1. 4) Finally, the deviation of each cylinder length from the desired length is calculated and the position control of each cylinder is done by a control scheme. By repeating the procedures 2)-4), the trajectory control can be carried out. All of the calculation including matrix A^{-1} are performed by a low-cost microcomputer. This microcomputer includes a clock frequency of 16MHz, ROM memory of 32kB, RAM memory of 2kB, 10bit A/D converter of 8ch and PWM port of 3ch.

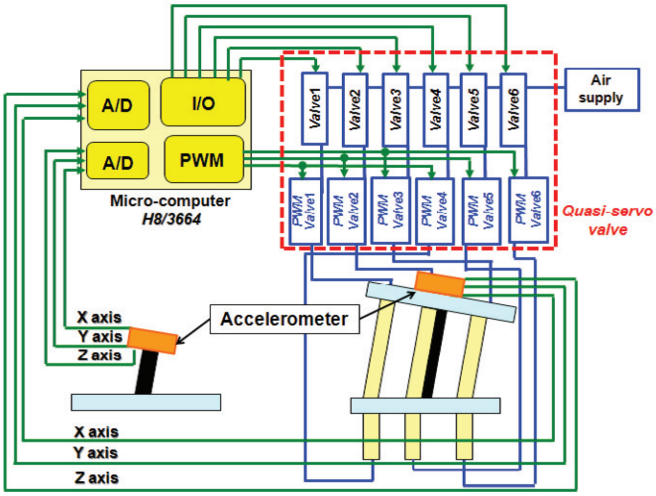


Fig. 4. Schematic diagram for control system

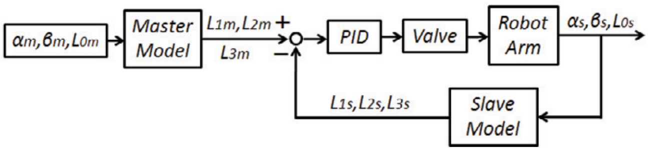


Fig. 5. Block diagram of master-slave control

5. Control Results and Discussion

5.1 Master slave control

For the master-slave control method by using the tested quasi-servo valve, the following typical PID control scheme was applied and embedded into the SH7125 microcomputer.

$$u_i = K_p e_i + K_I \int e_i dt + K_D \frac{de_i}{dt} \qquad \text{(i=1,2,3)} \qquad (14)$$

$$e_i = L_{im} - L_{is} \qquad \text{(i=1,2,3)} \qquad (15)$$

Where, u_i means the control input and e_i is the deviation of each cylinder length. K_P (=0.87[%/mm]), K_I (=2.5[%/mm/s]) and K_D (=0.0067 [% s/mm]) are the proportional gain, integral gain and the differential gain, respectively. These control parameters are adjusted based on the ultimate sensitivity method. Using the lower duty ratio as a control input to PWM valve, there exists the dead zone for output flow rate of the valve. Therefore, the input duty ratio of the PWM valve is always added to 23% from the absolute value of the control input which is calculated by Eq. (14). Furthermore, the state of switching valve (on or off) is decided by the sign (positive or negative) of the control input. Since this control method is embedded into the microcomputer, we can use the valve like a typical servo valve without complex operations. The control sampling period is 2ms, and the PWM period of the quasi-servo valve is 10ms.

Fig. 7 shows the transient responses of the length of each flexible cylinder L and bending direction angle α of the robot arm. The blue broken line shows the desired length of the virtual master flexible cylinder and the red solid line shows the slave flexible pneumatic cylinder length. During the experiment, the master arm is operated by a human hand to be bent, expanded and contracted. The frequency of the movement is about 0.2Hz as can be found in Fig. 7. From Fig. 7 also we can find that the slave arm can trace well the position of the master arm. Thus, we can confirm that the effectiveness of the control method can be achieved by using the proposed analytical model and the tested quasi-servo valve.

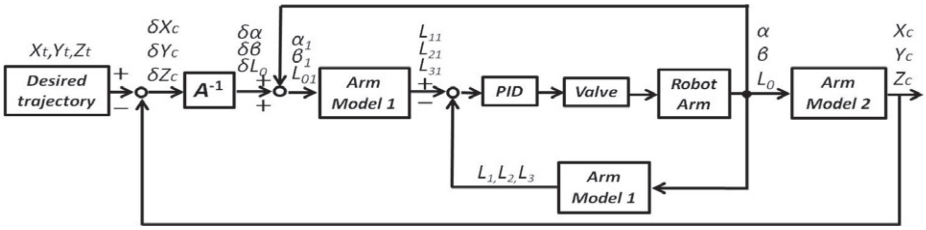


Fig. 6. Block diagram of trajectory control

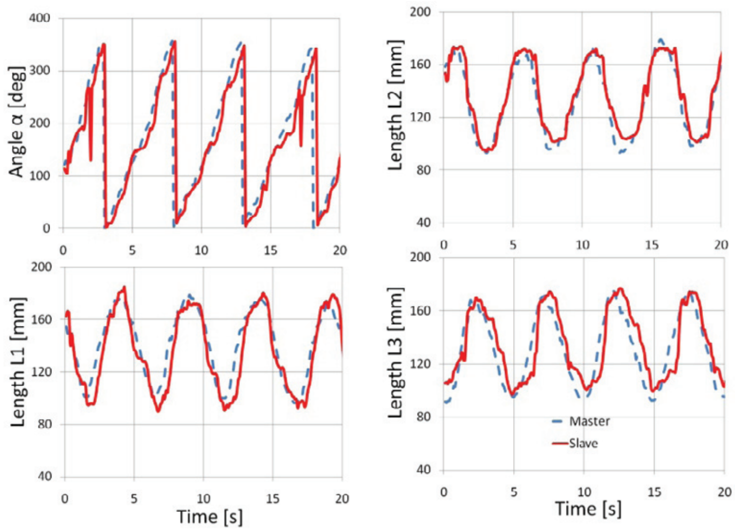


Fig. 7. Transient responses in master-slave control

5.2. Trajectory control

Fig. 8 shows the movement of the robot arm for a square-shaped trajectory. The arm end tries to track the desired square trajectory with the sides of 60mm, the constant height of 100mm and a constant moving speed of 6mm/s. The PID control scheme was used and the control parameters were same as ones in the master-slave control that was mentioned before. The sampling period also same which is 2ms and the PWM period is 10ms. During the control, the desired trajectory is updated every 3 samples. From Fig. 8 also, we can see the view of the robot arm from above and the red symbol ● shows the arm end position. As shown in the picture, the arm end moves as follows. First, the end position is at the initial position (X_c, Y_c, Z_c) = (0,0,100mm) and then it moves to (-30,-30,100) and stop for 2 seconds. Then, the arm end moves to positions (30,-30,100), (30, 30,100), (-30, 30,100) and (-30,-30,100) at a constant speed, and these movements are repeated.

Fig. 9 shows the experimental results of the trajectory control which are (a) and (b) show the track of the end position (X_c, Y_c) and the transient response of the position (X_c, Y_c, Z_c) respectively. In both figures, the blue broken line shows the desired position and the red solid line shows the calculated position. The red line is calculated in a microcomputer by using the proposed analytical model and the sensor output voltage. In Fig. 9, the trajectory from the initial position to a start position (-30,-30,100) is omitted. From Fig. 9(a), we can see that the robot arm tends to draw a square shape, but there are distinct large discrepancies from the desired position, especially at the corner of the square. This is be caused by the friction between the cylinder tube and the slide stage, and this friction becomes larger as the bending angle becomes larger. It is difficult to reduce the steady-state error due to a friction by a linear control scheme. Even though, from this figure, we still can examine that the overall controlled trajectory, the robot arm had moved same like the desired one. From Fig. 9(b), we can find that there are many small stepwise changes of the controlled end position. This is due to a stick-slip phenomenon caused by a friction of the cylinder. These movements seem to be suppressed to some extent in a wrist rehabilitation device, because a human hand is put on the robot arm as shown in Fig.1. However, the present control performance should be improved by decreasing a friction or by improving the control scheme. These improvements and application to a wrist for rehabilitation device will be our future works.

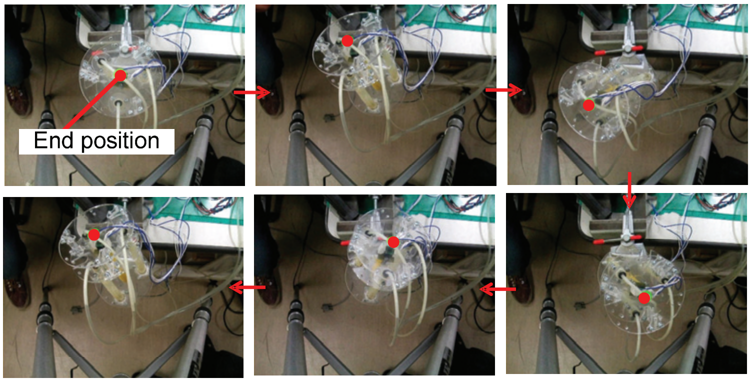


Fig. 8. View of movement of robot arm

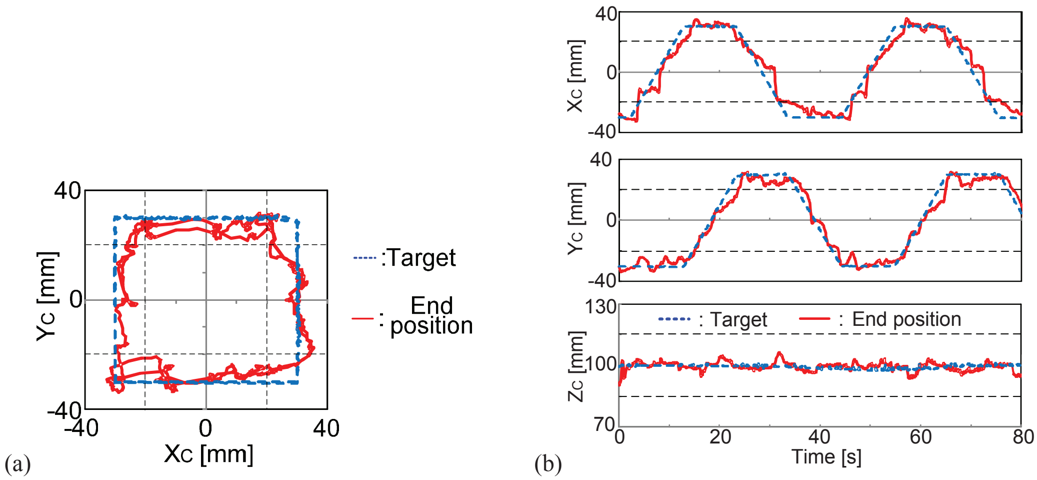


Fig. 9. Results of trajectory control for (a) robot arm end and (b) transient response of robot arm end

6. Conclusions

In this paper, pneumatic actuators with an inexpensive flexible cylinder and microcontroller are chosen for the development of the robot arm. The development of a simple-structured pneumatic robot arm and its control using low-cost embedded controller can be summarized as

1) The compact and inexpensive control system of the flexible robot arm for both master-slave control and trajectory control was proposed and tested. The system consists of the microcomputer, compact and inexpensive quasi-servo valves, accelerometers and the tested robot arm.

2) For the master-slave control system, a simple analytical model that can calculate the displacement of the flexible cylinder using the output voltage from the accelerometer was proposed. We also had proposed the analytical model and control procedure for the trajectory control system. In both controls method, all of the needed calculation and values can be obtained on time by using the high speed SH7125 microcomputer.

3) The master-slave control system and the trajectory control system were carried out by using the tested control system, the proposed control procedure and the PID control scheme. As a result, both tracking controls were realized and the effectiveness of the control method by using the proposed analytical model and the proposed control procedure was confirmed. However, the control performance should be improved because there exists relatively large control error caused by the friction of the cylinder.

Acknowledgements

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